

Time-Dependent AdS Backgrounds from S-Branes

Nihat Sadik Deger¹

Department of Mathematics, Bogazici University,
Bebek, 34342, Istanbul-Turkey

Feza Gursey Center for Physics and Mathematics,
Bogazici University, Kandilli, 34684, Istanbul-Turkey

ABSTRACT

We construct time and radial dependent solutions that describe p-branes in chargeless S-brane backgrounds. In particular, there are some new M5- and D3-branes among our solutions which have AdS limits and contain a cosmological singularity as well. We also find a time-dependent version of the dyonic membrane configuration in 11-dimensions by applying a Lunin-Maldacena deformation to our new M5-brane solution.

¹sadik.deger@boun.edu.tr

1 Introduction

One of the most profound ideas in String/M-theory is the AdS/CFT correspondence [1]. The original proposal of Maldacena was tested in various examples and extended to include different cases. However, understanding of this duality in time-dependent backgrounds is still incomplete. One important motivation to study this problem is to understand cosmological singularities like big bang using holography, see for instance [2], [3], [4]. Since AdS spacetimes appear as near horizon geometries of single and intersecting non-dilatonic p-branes, namely M2- and M5-branes in $d=11$ and D3-brane in $d=10$ (for a review see [5]), trying to add time dependence to them is a reasonable way to address this issue.

It is a well-known fact that one can replace the Minkowski geometry of the worldvolume of a p-brane with any Ricci-flat spacetime [6, 7] such as the time-dependent Kasner spacetime which is a natural choice to analyze the cosmological singularity problem. This was first considered in [8] for a D3-brane and this set-up was studied further in several other papers such as [9]-[14]. In [15] a more general solution where the D3-brane worldvolume is replaced by Friedmann-Robertson-Walker (FRW) metric with a conformal factor was obtained and its properties were analyzed [16]. For the M5-brane only the Kasner deformation has been investigated [17, 18].

In this letter we will show that the solutions mentioned in the previous paragraph are some specific examples of p-branes in chargeless S-brane backgrounds [19, 20, 21]. S-branes [22, 23, 24, 25, 26] are time-dependent analogs of p-branes and they may carry electric or magnetic charge similarly. However, unlike p-branes, the S-brane solution is still nontrivial when its charge vanishes. Various solutions describing S-brane intersections have been obtained [27, 28, 29, 30, 31]. Moreover, intersections between S- and p-branes were also studied [32, 33] but with the assumption that the S-brane has a nonzero charge. It was found in [32, 33] that solutions involving non-dilatonic p-branes were possible only with smearing in the transverse space, which destroys the AdS near-horizon geometry. In the next section we will demonstrate that relaxing the condition on S-brane charge results in a new set of solutions. In particular, we find that D3- and M5-brane solutions without smearing are allowed. It turns out that, there are two possible FRW type time-dependent D3-brane solutions and only one of which was known before [15]. The new one also has $AdS_5 \times S^5$ limit when the D3-brane worldvolume contains a hyperbolic part and a cosmological singularity as well. Yet, the two D3 configurations differ in the exponent of the string coupling at the singularity which could be important for its resolution [16]. For the M5-brane in addition to the Kasner case [17], we show that it is possible to have spherical or hyperbolic parts along the worldvolume directions too. The latter has an AdS limit like the D3-brane. In section 3, we provide another example of a cosmological AdS background by applying a Lunin-Maldacena deformation [34] to our M5-brane solution. This generates the time-dependent version of the dyonic M2-brane, $M2 \subset M5$, of [35] which has $AdS_7 \times S^4$ near-horizon too. This deformation is actually a particular U-duality transformation and a simple formula for the deformed background was given in [36] which we use here. We conclude in section 4 with some comments and possible future directions.

2 The Solution

The action in d -dimensions in the Einstein frame describing the bosonic sector of various supergravity theories containing the graviton g_{MN} , the dilaton ϕ coupled to the q -form field strength $F_{[q]} = dA_{[q-1]}$ with the coupling constant a is given as:

$$S = \int d^d x \sqrt{-g} \left(R - \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2(q)!} e^{a\phi} F_{[q]}^2 \right). \quad (1)$$

The Chern-Simons terms are omitted since they are irrelevant for our solutions. The field equations are:

$$\begin{aligned} R_{\mu\nu} &= \frac{1}{2} \partial_\mu \phi \partial_\nu \phi + \frac{1}{2(q)!} e^{a\phi} \left(q F_{\mu\alpha_2 \dots \alpha_q} F_{\nu}^{\alpha_2 \dots \alpha_q} - \frac{(q-1)}{d-2} F_{[q]}^2 g_{\mu\nu} \right), \\ \partial_\mu (\sqrt{-g} e^{a\phi} F^{\mu\nu_2 \dots \nu_q}) &= 0, \\ \frac{1}{\sqrt{-g}} \partial_\mu (\sqrt{-g} \partial^\mu \phi) &= \frac{a}{2(q)!} e^{a\phi} F_{[q]}^2. \end{aligned} \quad (2)$$

The field strength satisfies the Bianchi identity $\partial_{[\nu} F_{\mu_1 \dots \mu_q]} = 0$.

We are interested in finding solutions describing a p -brane in the presence of a chargeless S -brane without any smearing in p -brane's transverse space. The main result of this paper is that the above equations of motion admit such a solution:

$$\begin{aligned} ds^2 &= H^{-\frac{d-p-3}{d-2}} \left[e^{2\beta t} G_{n,\sigma}^{-\frac{1}{n-1}} (-G_{n,\sigma}^{-1} dt^2 + d\Sigma_{n,\sigma}^2) + \sum_{i=0}^{k-1} e^{2b_i t} dy_i^2 \right] \\ &+ H^{\frac{p+1}{d-2}} e^{-\frac{2\gamma\epsilon a}{d-p-3} t} (dr^2 + r^2 d\Omega_m^2), \\ \phi &= \epsilon a \ln H + \gamma t, \\ F_{t1\dots pr} &= Q^*[\text{Vol}(\Omega_m)] \text{ (Electric)}, \quad F_{1\dots m} = Q \text{Vol}(\Omega_m) \text{ (Magnetic)}, \end{aligned} \quad (3)$$

where $\text{Vol}(\Omega_m)$ is the volume form of the m -dimensional unit sphere Ω_m and the symbol “ $*$ ” denotes the Hodge dual operation with respect to full metric. Here $p = n + k$ and the function H is the harmonic function of the $(m+1)$ -dimensional flat transverse space

$$H = 1 + \frac{Q}{r^{m-1}}. \quad (4)$$

For the D3-brane its 5-form field strength should be self-dual. In the metric above, $d\Sigma_{n,\sigma}^2$ represents the metric on the n -dimensional unit hyperbola, unit sphere or flat space and the function $G_{n,\sigma}$ is defined respectively as:

$$G_{n,\sigma} = \begin{cases} M^{-2} \sinh^2 [(n-1)M(t-t_0)], & \sigma = -1 \quad (\text{hyperbola}), \\ M^{-2} \cosh^2 [(n-1)M(t-t_0)], & \sigma = 1 \quad (\text{sphere}), \\ \exp[2(n-1)M(t-t_0)], & \sigma = 0 \quad (\text{flat}). \end{cases} \quad (5)$$

Finally, constants should satisfy

$$\begin{aligned}\beta &= -\frac{1}{n-1} \left(\sum_{i=0}^{k-1} b_i - \frac{(m+1)\gamma\epsilon a}{d-p-3} \right), \\ n(n-1)M^2 &= (n-1)\beta^2 + \sum_{i=0}^{k-1} b_i^2 + \frac{(m+1)\gamma^2 a^2}{(d-p-3)^2} + \frac{\gamma^2}{2}.\end{aligned}\quad (6)$$

It is understood that when $k = 0$ then, all b_i 's are zero. We should also have² $n \geq 2$ and $m \geq 2$. The constant Q is the charge of the p-brane and t_0 is another constant related to the S-brane³.

If we set all time-dependent parts to zero⁴, then this solution is nothing but the well-known p-brane solution, for a review see [5]. The dilaton coupling 'a' is zero in 11-dimensional supergravity and in type *IIA* and *IIB* supergravities it is given as:

$$\begin{cases} \epsilon a = \frac{3-p}{2}, & RR\text{-branes} \\ \epsilon a = \frac{p-3}{2}, & NS\text{-branes} \end{cases}\quad (7)$$

where $\epsilon = 1$ for electric branes ($p = 0, 2$ in type *IIA* and $p = 1$ in type *IIB*) and $\epsilon = -1$ for magnetic branes ($p = 4, 6$ in type *IIA* and $p = 5$ in type *IIB*).

On the other hand, if we remove all radial dependence by setting the p-brane charge to zero, i.e. $Q = 0$, then what is left is the vacuum S-brane solution [19, 20, 21]. Therefore, our new solution (3) can be thought of as a superposition of a p-brane with a chargeless S-brane.

Although, intersections between S- and p-branes were studied before in [32, 33], this solution was missed because in those papers S-brane was assumed to have a charge to begin with. The intersection dimension and the amount of smearing for the p-brane depends crucially on the existence of the S-brane charge and taking the zero charge limit at the end does not reproduce the above solution. It turns out that, in almost all the solutions found in [32, 33] there has to be some smearing⁵. In particular, this is the case for all non-dilatonic p-branes which we now demonstrate explicitly. In such configurations the dilaton and the field strenghts are written as summations of those corresponding to S- and p-branes with appropriate r and t dependent coefficients and in the metric multiplicative separation of variables is assumed:

$$\begin{aligned}ds^2 &= -e^{2A(t)}e^{2\alpha(r)}dt^2 + e^{2B(t)}e^{2\alpha(r)}d\Sigma_{n,\sigma}^2 + e^{2C(t)}e^{2\alpha(r)}(dx_0^2 + \dots + dx_{k-1}^2) \\ &+ e^{2E(t)}e^{2\theta(r)}(dy_1^2 + \dots + dy_c^2) + e^{2D(t)}e^{2\theta(r)}(dr^2 + r^2d\Omega_{m-c}^2).\end{aligned}\quad (8)$$

The p-brane is located at $(t, \Sigma_{n,\sigma}, x_0, \dots, x_{k-1})$. The directions (y_1, \dots, y_c) are smeared for the p-brane which has $(m - c + 1)$ dimensional localized transverse space. Here $\Sigma_{n,\sigma}$ is

²When $\sigma = 0$, having different time-dependent exponentials for $\Sigma_{n,0}$ directions is also possible.

³It is possible to add more additive constants in the exponentials multiplying dy_i^2 in the metric.

⁴Note that this enforces $\sigma=0$, since when $\sigma \neq 0$ there are inverse powers of the constant M in (5).

⁵Even when there is no smearing, the zero charge limit only gives the $\sigma = 0$ case with all b_i 's equal.

the intersection manifold with the S-brane which should be flat when the S-brane has charge. The radial metric functions are those of a p-brane, namely $e^{2\alpha} = H^{-\frac{d-p-3}{d-2}}$ and $e^{2\theta} = H^{\frac{p+1}{d-2}}$ where the harmonic function H is given before (4). With these choices field equations for radial and time-dependent parts decouple and one ends up with the usual S- and p-brane equations [33]. The number of intersection n and smearing c are fixed by solving the field equation for the non-diagonal Ricci tensor component:

$$R_{tr} = (d - 2 - c)\alpha' \dot{D} + c[\alpha' \dot{E} + \theta'(\dot{D} - \dot{E})] , \quad (9)$$

where prime and dot correspond to r and t differentiations respectively. Now the S- and p-brane form fields in general do not contribute to the R_{tr} component of the Einstein field equations (2), only the dilaton contributes [33]. Let us assume that there is no smearing, i.e. $c = 0$, which needs to be the case if we want to keep the AdS near horizon geometry of a non-dilatonic p-brane, for which $a = 0$, intact. From (9) it is clear that we should have $\dot{D} = 0$. However, a time independent metric part in the general S-brane solution is not allowed when it is charged [25] but it is possible when it is chargeless [36]. Therefore, when S-brane has a charge, there has to be some smearing for a non-dilatonic p-brane. For example, in the M5-SM2 intersection we need $c = 2$ or $c = 1$ depending on whether radial part of M5-brane is included in the worldvolume of SM2 or not, respectively [33].

General properties of these solutions related to time dependence are similar to usual S-branes [26, 27]. First of all, note that one of the constants $\{M, \beta, \gamma, b_i\}$ can be set to 1 by rescaling the time coordinate. There are generic singularities as $t \rightarrow \pm\infty$ as can be seen from the collapse of some of the metric functions. When t is finite, time-dependent metric functions are well-behaved except the $G_{n,-1}$ function (5) which becomes zero at $t = t_0$. However, this is not a singularity; by defining a new coordinate $u = (t - t_0)^{-1/2}$ we get $-du^2 + u^2 \Sigma_{n,-1}$ which is just the flat spacetime in Rindler coordinates. Hence, for $\sigma = -1$ we have $t \in (t_0, \infty)$ or $(-\infty, t_0)$ whereas for $\sigma = \{0, 1\}$ we have $t \in (-\infty, \infty)$. Finally, in the general solution (3) it is possible to smear some directions from the $(m+1)$ -dimensional transverse space. For example, smearing one direction one has to do the replacement: $H^{\frac{p+1}{d-2}}(dr^2 + r^2 d\Omega_m^2) \rightarrow H^{\frac{p+1}{d-2}}(dz^2 + d\tilde{r}^2 + \tilde{r}^2 d\Omega_{m-1}^2)$. The harmonic function H is independent of the z -coordinate. Now, we would like to concentrate on the solutions for non-dilatonic p-branes, namely M2 and M5-branes in $d=11$ and, D3-brane in $d=10$, since they have AdS near horizon limits.

2.1 Non-dilatonic p-branes

For non-dilatonic p-branes we have $a = 0$ and notice that in that case time dependence in the metric (3) appears only in the worldvolume directions. It is a well-known fact that one can replace the Minkowski geometry the worldvolume of a p-brane with any Ricci-flat spacetime [6, 7]. Hence, when also the constant $\gamma = 0$ in (3), which is necessarily the case in $d=11$, our solutions just corresponds to this fact. But, otherwise the worldvolume replacement is not Ricci flat.

One remarkable property of the solution that we found is that (3) it gives M5 and D3-branes in a time-dependent background. However, M2-brane is not allowed. To see

why, note that when the constant $\gamma = 0$, the equation (6) implies that at least one of the b_i 's have to be nonzero, in other words $k \geq 1$. Combining this with the condition $n \geq 2$ this implies $p \geq 3$ and hence M2-brane solution in d=11 is not possible. From this argument it also follows that for the D3-brane $2 \leq n \leq 3$ and for the M5-brane $2 \leq n \leq 4$.

Now let us focus on the near horizon $r \rightarrow 0$ region of the D3-brane. For $n = 3$ this solution was obtained before for $\sigma = 0$ in [8] and for $\sigma \neq 0$ in [15]. On the other hand, for $n = 2$ only $\sigma = 0$ case was considered before [8]. It is obvious that when $\sigma = 0$ both of these solutions approach to $AdS_5 \times S^5$ geometry as $t \rightarrow t_0$. In this limit, also for $\sigma = -1$ the D3-worldvolume is conformal to parts of the Minkowski spacetime and hence is appropriate for studying time-dependent AdS/CFT correspondence too [15]. For $n = 3$ this follows immediately, since in this limit the D3 worldvolume becomes Rindler spacetime from the discussion above. For $n = 2$, the same argument works as well or one can see this more concretely by making change of variables⁶ as in [15]. There is an important difference between these two solutions in terms of the value of the constant γ , which plays a crucial role in the string coupling $e^\phi = e^{\gamma t}$. Notice that for $\sigma = -1$, e^ϕ is bounded unlike the $\sigma = 0$ case and as we approach to the AdS boundary via $t \rightarrow t_0$, it becomes constant. Note that for $n = 3$ we have $12M^2 = \gamma^2$ and for $n = 2$ we have $4M^2 = 4\beta^2 + \gamma^2$ from (6). Setting $M = 1$ by rescaling the time coordinate, we see that $\gamma = 2\sqrt{3}$ for $n = 3$, whereas γ can take any value from the interval $[0, 2]$ when $n = 2$. As we approach to the singularity at $\tau = -\infty$ in both $n = \{2, 3\}$ cases the string coupling asymptotes to zero. In [16] it was argued that the singularity becomes better when the exponent in the string coupling is less than 1, which is possible only when $n = 2$.

Similar arguments also work for the M5-brane where one gets $AdS_7 \times S^4$ geometry for $\sigma = -1$ and $\sigma = 0$ as $t \rightarrow t_0$. For M5-brane only the $\sigma = 0$ case was known before [10].

3 Lunin-Maldacena Deformation of the Time Dependent M5-brane

An important feature of S-branes is that they give rise to accelerating cosmologies upon compactification [19]. When their charge is zero, as in the above solutions, this happens only when $\sigma = -1$, whereas for a charged S-brane there is no such restriction [20]. Hence, it is desirable to find a solution with a charged S-brane which has an AdS limit to study acceleration from the dual field theory point of view. To obtain such a solution, we recall a result of [21] where it was shown that applying a Lunin-Maldacena deformation [34] to a chargeless S-brane solution in d=11, one gets a charged SM2-brane. We now employ this idea to our time-dependent M5-brane solution.

In [36] a simple formula was derived to obtain Lunin-Maldacena deformations [34] of solutions of d=11 supergravity which possess three $U(1)$ isometries. The formula given in [36] is valid only when these $U(1)$ directions do not mix with any other coordinate in the metric and when the 4-form field strength has at most one overlapping with them.

⁶To put our metric into the form used in [15] one should define $e^{(n-1)M(t-t_0)} = |\tanh \frac{(n-1)\tau}{2}|$.

Since the metric of our M5-brane solution is diagonal, the first condition is automatically satisfied and hence we just need to be careful about the second one. Now, the 4-form field strength of the M5-brane has directions in the transverse part and therefore we have only two possibilities for choosing the $U(1)$ directions: 1 from transverse and 2 from the worldvolume or all of them from the worldvolume. Only the second choice gives rise to a new solution as we explain below. For the first one, we need a smearing in the transverse space which is always possible in (3) as explained before. For the M5-brane suppose we do this smearing and let there be at least two y_i directions in (3). Then, using these two y_i 's and the smeared direction one gets a charged SM2-brane as was already observed in [21]. This is nothing but a generalization of the M5-SM2 solution found in [33] since we now allow hyperbolic or spherical Σ 's on the worldvolume of the p-brane. Because of the smearing, there is no AdS limit. For the second set of $U(1)$'s, let us now take the M5-brane without any smearing and choose $n = 2$ in (3). We can now use the remaining 3 worldvolume directions $\{y_0, y_1, y_2\}$ to perform Lunin -Maldacena deformation [34] which upon applying the method of [36] leads to:

$$\begin{aligned}
ds^2 &= H^{-\frac{1}{3}} \left[K^{-\frac{1}{3}} e^{2\beta t} G_{2,\sigma}^{-1} (-G_{2,\sigma}^{-1} dt^2 + d\Sigma_{2,\sigma}^2) + K^{\frac{2}{3}} \left(\sum_{i=0}^2 e^{2b_i t} dy_i^2 \right) \right] \\
&+ H^{\frac{2}{3}} (dr^2 + r^2 d\Omega_4^2) \quad , \\
\tilde{F}_{[4]} &= Q \text{Vol}(\Omega_4) - \alpha i_0 i_1 i_2 * [Q \text{Vol}(\Omega_4)] + \alpha d(K H^{-1} e^{-2\beta t} dy_0 \wedge dy_1 \wedge dy_2) \quad , \\
K &= [1 + \alpha^2 H^{-1} e^{-2\beta t}]^{-1} \quad , \quad \beta = -(b_0 + b_1 + b_2) \quad ,
\end{aligned} \tag{10}$$

where the Hodge dual $*$ is with respect to the undeformed metric and i_m stands for the contraction with respect to the isometry direction y_m . Here α is the deformation parameter and when $\alpha = 0$ we have the original time-dependent M5-brane solution. From $\tilde{F}_{[4]}$ we see that there is an M2-brane located at $\{t, \Sigma_{2,\sigma}\}$ and a *static* SM2 located at $\{y_0, y_1, y_2\}$ whose 4-form field has a leg in r . When $\beta \neq 0$ we also have a regular SM2-brane again at $\{y_0, y_1, y_2\}$. Note that all additional branes are entirely inside the M5-brane. When all time dependence is removed this solution is just the dyonic solution $M2 \subset M5$ obtained in [35]. Note that in the near horizon limit $r \rightarrow 0$ for any finite t the function $K \rightarrow 1$. Hence, we again have the $AdS_7 \times S^4$ geometry for $\sigma = -1$ and $\sigma = 0$ as $t \rightarrow t_0$ and there is a cosmological singularity at infinity, like the single time-dependent M5-brane. Having an SM2-brane in the configuration is especially attractive since compactifying on to its worldvolume results in an accelerating 4-dimensional spacetime [19, 20].

4 Discussion

In this letter we have constructed a large class of new exact solutions in type II and $d=11$ supergravities. Only some special cases of those corresponding to D3- and M5-branes were known before. However, their relation to S-branes was not realized. This opens up a whole new line of investigation since hyperbolic compactifications of chargeless S-branes produce a short period of accelerating cosmologies [19]. Our time-dependent M5-brane solution with $n = 2$ and $\sigma = -1$ and the solution (10) that we found in section 3 are especially

suitable to study this phenomena using the AdS/CFT duality. There are of course many other aspects of this correspondence that one would like to understand better in time-dependent backgrounds and we expect our new solutions to be useful in studying them. For our solutions, understanding the decoupling of their worldvolume theories from the bulk [37] and studying the fate of cosmological singularity using the gauge theory picture are especially important.

As a side result, our work also shows that the S- and p-brane intersections found in [33] where the S-brane was charged, can be generalized so that the p-brane worldvolume directions not intersecting with the S-brane can be taken curved if their total dimension is greater than 1.

Intersections of the dyonic membrane solution [35] was studied in [38]. Repeating this for our time-dependent version (10) is desirable. Moreover, it is possible to add waves and Kaluza-Klein monopoles to p-branes [39] and S-branes [40]. It would be interesting to investigate whether this is allowed for solutions found in this paper.

Studying black holes in a time-dependent AdS background is another very intriguing challenge. Intersections of p-branes can be used to describe black holes in four and five dimensions [41, 42] which have AdS near horizons. In [40] it was shown that adding a charged S-brane to these configurations is not possible. Nevertheless, our current work suggests that it is worth revisiting this question for a chargeless S-brane. We hope to investigate these problems in near future.

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